Intercepted Photosynthetically Active Radiation Estimated by Spectral Reflectance*

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Interception of photosynthetically active radiation (PAR) was evaluated relative to greenness and normalized difference [MSS $(7-5)/(7+5)$] for five planting dates of wheat for 1978–79 and 1979–80 at Phoenix, Arizona. Intercepted PAR was calculated from leaf area index and stage of growth. Linear relationships were found with greenness and normalized difference with separate relationships describing growth and senescence of the crop. Normalized difference was significantly better than greenness for all planting dates. For the leaf area growth portion of the season the relation between PAR interception and normalized difference was the same over years and planting dates. For the leaf senescence phase the relationships showed more variability due to the lack of data on light interception in sparse and senescing canopies. Normalized difference could be used to estimate PAR interception throughout a growing season.

Introduction

Crop yield models require an estimate of either the leaf area index (LAI) or the amount of intercepted photosynthetically active radiation. Biscoe et al. (1975) showed that dry matter production by barley canopies was driven by the intercepted radiation. Hodges and Kanemasu (1977) used a conversion factor from intercepted radiation to dry matter production in their wheat model. Daughtry et al. (1983) showed conceptually how remotely sensed data could be used to obtain an estimate of the solar radiation intercepted by canopies and then converted to dry matter. Steven et al. (1983) found that the ratio of near-infrared/red radiation was related to rate of growth in sugarbeets and showed that this ratio was related to interception of light by the canopy. They suggested that this procedure would be valuable for the remote assessment of crop growth. Thus, it would appear that an estimate of intercepted radiation by canopies from a remote sensing platform would be desirable for monitoring crop growth.

Kollenkark et al. (1982) found that greenness and LAI were strongly related; however, they showed an even stronger relationship between soil cover and greenness for soybeans. They also showed that greenness reached a maximum, although LAI continued to increase suggesting that at the upper values of leaf area index greenness may be saturating. Daughtry et al. (1983) also showed a similar relationship in their corn data, which

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suggests that greenness may not be directly related to LAI.

Pinter et al. (1981) found that normalized difference when integrated over time from heading until maturity of wheat was related to yield. They suggested that this integration would represent the duration of green leaf area by a crop and thus be directly transferable to yield. This approach was extended by Hatfield (1983), in which canopy temperature was used to evaluate the impact of stress on yield and a spectrally derived LAI at heading was used to determine the potential yield. Wiegand et al. (1979) showed how remotely derived leaf area indices could be used in evapotranspiration or crop yield models and suggested that these remotely obtained estimates would allow crop models to be applied on a regional basis.

This study was conducted to evaluate the possibility of using spectral reflectance to estimate intercepted radiation in wheat.

Materials and Methods

Produra wheat (*Triticum aestivum* Desf. var. Produra) was grown at the U.S. Water Conservation Laboratory, Phoenix, Arizona during the 1978–79 and 1979–80 growing season. The treatments were five planting dates and three or four irrigation treatments within a planting date. The plots were planted in north–south rows in an Avondale loam [fine loamy, mixed (calcareous), hyperthermic Anthropic Torrifluvent].

Reflectance measurements were made over each plot on every non-rainy day with the sun at an elevation of 33°. In the final analysis, data from completely overcast days were removed from the data set. These data were collected with a four-band hand-held Exotech Model 100-A Radiometer equipped with the four Landsat MSS bands. Data were collected with the radiometer held 2 m above the soil surface. Each day was given a quality rating depending upon the cloud conditions, instrument operation, and general meteorological conditions, and only days of the highest quality were used in this study.

From the reflectance data greenness was calculated using the equation given by Rice et al. (1980) as

$$\begin{aligned} \text{greenness} = &-0.4984\ \text{MSS4} \\ &-0.6125\ \text{MSS5} \\ &+0.1729\ \text{MSS6} \\ &+0.5854\ \text{MSS7}, \end{aligned} \tag{1}$$

where MSS4 is the reflectance in band 4 (0.5–0.6 μm), MSS5 band 5 (0.6–0.7 μm), MSS6 band 6 (0.7–0.8 μm), and MSS7 in band 7 (0.8–1.1 μm). Jackson (1983) described an alternative approach for the calculation of greenness, and, although these values for the Avondale loam are slightly different, we chose to use those by Rice et al. (1980) because of their current usage by a number of agencies. Normalized difference vegetation index was calculated as

$$ND = \frac{\text{MSS7} - \text{MSS5}}{\text{MSS7} + \text{MSS5}}. \tag{2}$$

Twice weekly in each treatment six plants were randomly selected, and the green and brown leaf area was measured. These data were then used to compute the leaf area index (LAI) for each treatment.

Intercepted photosynthetically active radiation (PAR) was calculated for each day as described by Hipps et al. (1983).

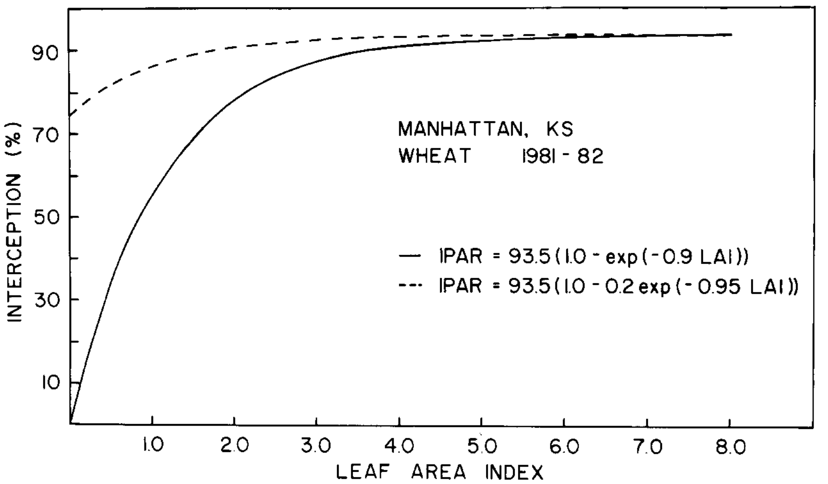

FIGURE 1. Interception of photosynthetically active radiation for preheading phase (—) and postheading phase (--) of wheat as a function of leaf area index. Derived from Hipps et al. (1983).

In their study they measured the interception of PAR by wheat canopies at various stages of growth up until heading. These measurements were made with quantum sensors positioned above and below the canopy with simultaneous measure of LAI in each variety. Their relationship was only applicable to the description of interception until maximum LAI was reached (heading). Additional data collected in the manner described by Hipps et al. (1983) were analyzed to determine the interception–LAI relationship over the postheading period of wheat. These relationships are given in Fig. 1 and were used to calculate the amount of PAR intercepted by the Produra canopy for each treatment in this study. Although the varieties were different between the relationship developed by Hipps et al. (1983) and this study, we used their relationship because there was little difference between their varieties and the relationship was transferable to data collected in California on another variety by the senior author.

Results and Discussion

Greenness–interception relationships

Interception of photosynthetically active radiation by a canopy is dependent upon the age of the plant as shown in Fig. 1. When leaves are being developed, the interception relationship rises very rapidly, while under senescence, the interception declines very slowly and only returns to values above 50%. At physiological maturity when the leaves are senescent, PAR interception would be dependent on the amount of biomass remaining on a unit area of soil, e.g., a sparse canopy when mature would allow more PAR penetration than would a very dense canopy. The temporal behavior of greenness for the well-watered plots of 1978–79 also exhibits patterns similar to the interception of PAR (Fig. 2). Throughout this report only data from well-watered plots are shown because they are typical in this study and show the relationship between interception and the spectral estimators. For all planting dates

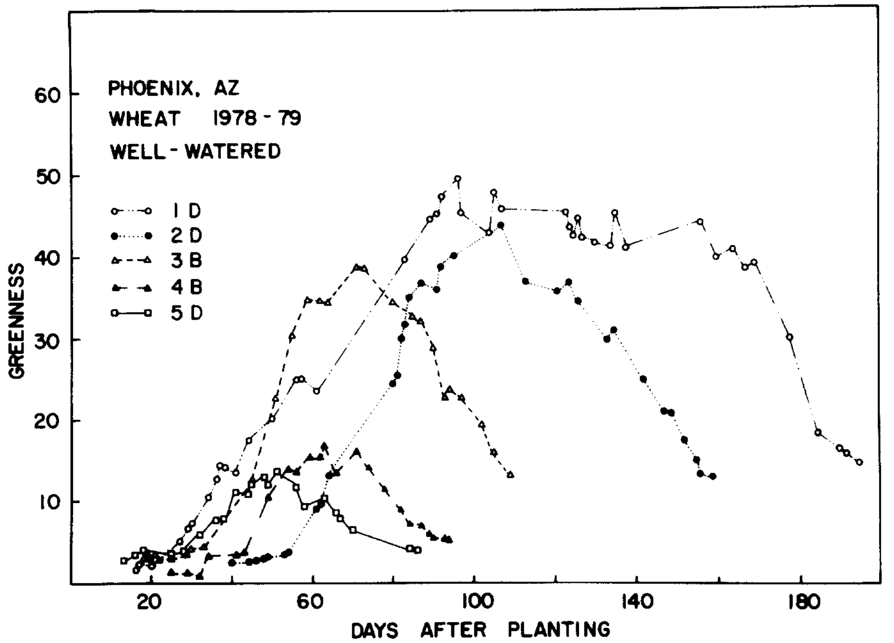

FIGURE 2. Temporal behavior of greenness for the well-watered plots of Produra wheat grown in 1978–79 planting dates in Phoenix.

the greenness values began at the same value but returned to different levels at maturity, with the greenness level at maturity dependent upon the amount of total standing biomass (grain and straw). The relationship of greenness with LAI and intercepted PAR for one irrigation treatment is shown in Fig. 3. Although LAI increased above 4, greenness maintained a stable value much in line with PAR interception. Greenness declined when PAR interception decreased at the end of the season (Fig. 3). With the apparent differences between the preheading and postheading portion of the season the regression models between intercepted PAR and greenness were also obtained for the two growth stages.

The linear correlations between intercepted PAR and greenness were highly significant for all planting dates except planting date 5 in 1978–79 (Table 1). This planting date had very low PAR interception values and the poor correlation is due to a limited range of interception and LAI values. These data, however, did not detract from the overall relationship (Table 1). The standard errors for the slope of the regression models were small. There was no statistical difference between the combined models for each year. The regression statistics for the data combined over years also shows the same values as each individual year (Table 1). The correlation coefficients for regression models between intercepted PAR and greenness for the senescence portion of the growth period were not as high as those for the vegetative period, and the greatest difference was seen in the intercept values (Table 2). Overall, there was more variation between planting dates; however, the combined models over years were not different (Table 2). The reason

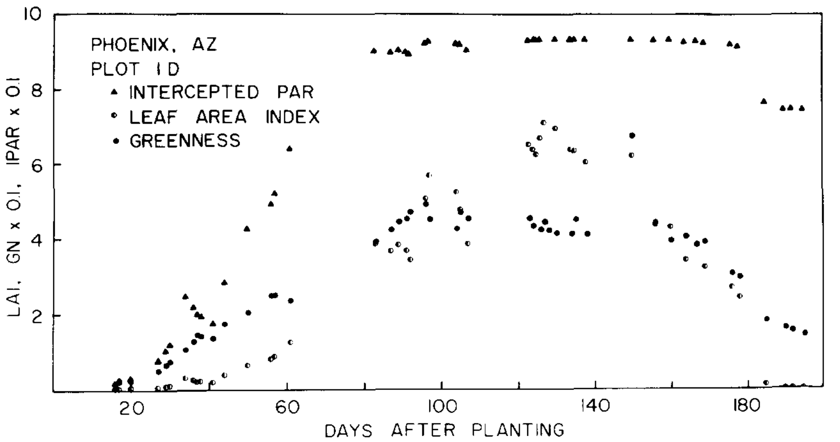

FIGURE 3. Intercepted PAR, leaf area index, and greenness for the 31 October 1978, planting date of Produra wheat maintained in a well-watered condition.

TABLE 1 Regression Coefficients for the Linear Model of Greenness and PAR Interception from Planting until Maximum Area Index for the 1978–79 and 1979–80 Planting Dates of Produra Wheat at Phoenix

Year	Planting Date	n	R^2	Intercept	Slope (b)	s.e.[b]
1978–79	1	116	0.98	−2.54	2.17	0.03
	2	80	0.95	−1.16	2.34	0.06
	3	64	0.96	−2.87	2.58	0.07
	4	30	0.83	−1.43	2.22	0.19
	5	32	0.47	−0.02	1.59	0.31
	combined	322	0.96	−1.46	2.24	0.03
1979–80	1	63	0.81	−3.99	3.04	0.19
	2	69	0.94	−1.44	2.13	0.06
	3	45	0.96	−3.27	2.08	0.06
	4	28	0.98	1.55	1.91	0.05
	5	24	0.99	−0.36	2.10	0.05
	combined	229	0.88	3.02	2.06	0.05
	combined years	551	0.92	−0.98	2.18	0.04

fcr the lack of fit on planting dates 5 of 1978–79 and 1 of 1979–80 can be attributed to a lack of fit of the PAR interception relationship given in Fig. 1. These data shown in Fig. 1 do not represent biomass values as low as those encountered in these planting dates. Other relationships more representative of this range of data and stage of development would possibly improve the greenness–PAR interception relationship.

Normalized difference–interception relationship

Trajectories of the normalized difference throughout 1978–79 for the well-watered irrigation treatments of each planting date revealed that the normalized difference behaved similarly to PAR interception (Fig. 4). Normalized difference and PAR interception appear to be very closely related as shown in Fig.

TABLE 2 Regression Coefficients for the Linear Model of Greenness and PAR Interception from Maximum Leaf Area Index until Maturity for the 1978–79 and 1979–80 Planting Dates of Produra Wheat at Phoenix

Year	Planting Date	n	R^2	Intercept	Slope (b)	s.e. b
1978–79	1	76	0.88	67.41	0.62	0.03
	2	60	0.93	65.05	0.77	0.03
	3	48	0.89	68.86	0.67	0.04
	4	42	0.76	70.40	0.62	0.05
	5	64	0.41	75.21	0.21	0.03
	combined	290	0.85	71.55	0.52	0.01
1979–80	1	21	0.33	78.27	0.36	0.12
	2	21	0.96	65.05	0.74	0.03
	3	24	0.90	66.87	0.58	0.04
	4	32	0.83	66.77	0.62	0.05
	5	40	0.92	65.82	0.66	0.03
	combined	138	0.80	67.93	0.61	0.03
	combined years	428	0.84	69.05	0.55	0.02

5 for a well-watered treatment from 1978–79. The relationship between normalized difference and intercepted PAR (Fig. 6) closely followed the relationship given in Fig. 1. When the regression coefficients were computed for each planting date and growth phase, the R^2 values were greater than those for greenness. For the period from emergence to maximum leaf area index only planting date 5 of 1978–79 did not show a larger R^2 for the normalized difference (Table 3). There was no statistically significant difference between the years when the planting dates were combined and the regression model when combined over years (Table 3).

There was more difference between years and planting dates in the relationships between normalized difference and PAR interception for the postheading phase (Table 4). This can be attributed to a lack of an exact function that describes the PAR interception–LAI relationship, particularly in low biomass plots. Al-

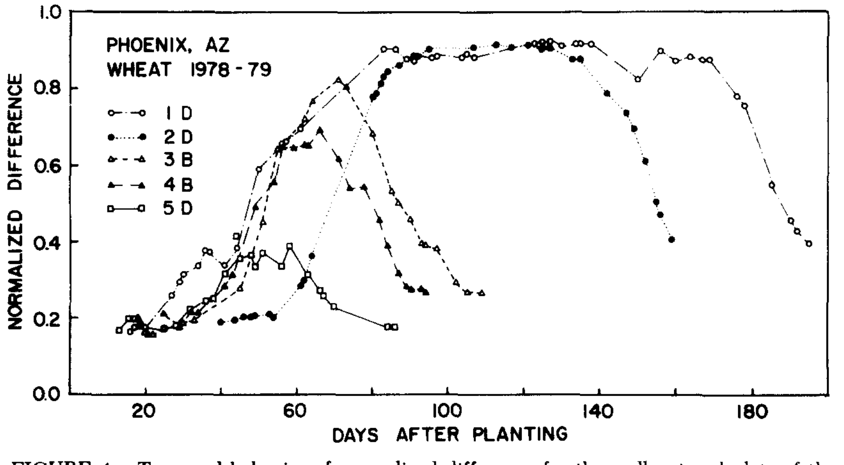

FIGURE 4. Temporal behavior of normalized difference for the well-watered plots of the 1978–79 planting dates of Produra wheat in Phoenix.

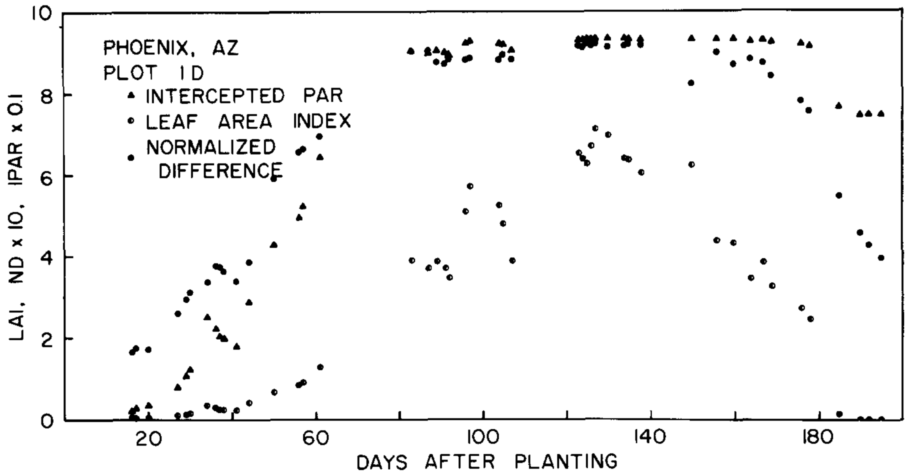

FIGURE 5. Intercepted PAR, leaf area index, and normalized differences for the 31 October 1978 planging date of Produra wheat maintained in a well-watered condition.

though the normalized difference values are related to PAR interception, there was considerable variation between the regression lines for the different planting dates. These data show that research is needed to further refine these relationships for the postheading phase of growth.

Normalized differences did not exhibit any bias for the growth phase with a range of PAR interception values (Fig. 7). There were more data for the extremes in the data set with the greater variation in the midrange. The greatest scatter was in the senescence phase, and particularly at the lower normalized difference values (Fig. 8). This variation is due to the inadequacy of the LAI–interception relationship at low biomass values.

Pinter et al. (1981) showed that the normalized difference could be integrated

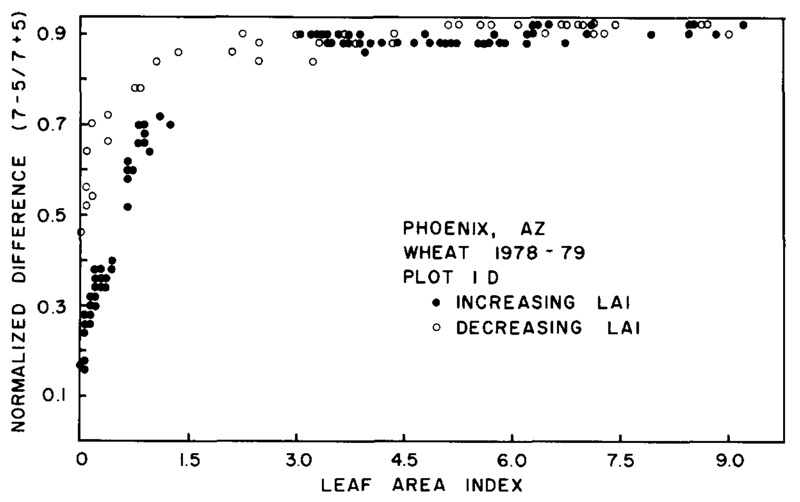

FIGURE 6. Normalized difference as a function of leaf area index for the 1978–79 Produra wheat treatment 1D.

TABLE 3 Regression Coefficients for the Linear Model of the Normalized Difference and PAR Interception from Emergence until Maximum Leaf Area Index for the 1978–79 and 1979–80 Planting Dates of Produra Wheat at Phoenix

Year	Planting Date	n	R^2	Intercept	Slope (b)	s.e. b
1978–79	1	116	0.98	−23.56	127.41	1.49
	2	80	0.98	−17.99	117.63	1.88
	3	64	0.95	−17.40	121.52	3.59
	4	30	0.87	−13.47	105.56	7.66
	5	32	0.29	−6.88	68.10	19.42
	combined	322	0.97	−18.40	120.03	1.11
1979–80	1	63	0.87	−14.06	122.30	6.14
	2	69	0.96	−20.43	121.10	3.12
	3	45	0.98	−19.94	120.34	2.27
	4	28	0.99	−33.01	136.85	2.09
	5	24	0.98	−27.86	127.31	3.76
	combined	229	0.95	−19.74	122.35	1.92
	combined years	551	0.97	−18.79	121.04	1.60

with time and related to the yield of wheat. They postulated that this would represent a measure of the leaf area duration; however, these data suggest that an integration of the normalized difference represents a measure of the ability of a canopy to intercept PAR and thus is directly related to plant productivity. This type of relationship was shown to be valid by Steven et al. (1983). Daughtry et al. (1982) also showed that solar radiation interception by corn could be approximated by greenness. They proposed a seasonal integration method to arrive at final yield of the crop. It appears that the normalized difference, which requires no derived coefficients, is more applicable than greenness to the evaluation of intercepted PAR. However, greenness–PAR interception relationships could be improved by using a greenness model developed for the Avondale loam soil at Phoenix. Differences, however, would be small because the calculated coefficients

TABLE 4 Regression Coefficients for the Linear Model of the Normalized Difference and PAR Interception from Maximum Leaf Area Index until Maturity for the 1978–79 and 1979–80 Planting Dates of Produra Wheat at Phoenix

Year	Planting Date	n	R^2	Intercept	Slope (b)	s.e. b
1978–79	1	76	0.93	59.77	36.44	1.12
	2	60	0.96	61.24	34.33	0.91
	3	48	0.90	67.02	28.42	1.36
	4	42	0.82	68.69	25.00	1.85
	5	64	0.39	74.25	9.74	1.55
	combined	290	0.87	68.41	25.71	0.59
1979–80	1	21	0.87	60.94	36.38	3.18
	2	21	0.97	60.35	36.05	1.44
	3	24	0.92	59.58	35.96	2.27
	4	32	0.89	59.29	37.53	2.44
	5	40	0.95	58.83	36.95	1.39
	combined	138	0.92	59.50	36.89	0.90
	combined years	438	0.89	59.50	36.89	0.90

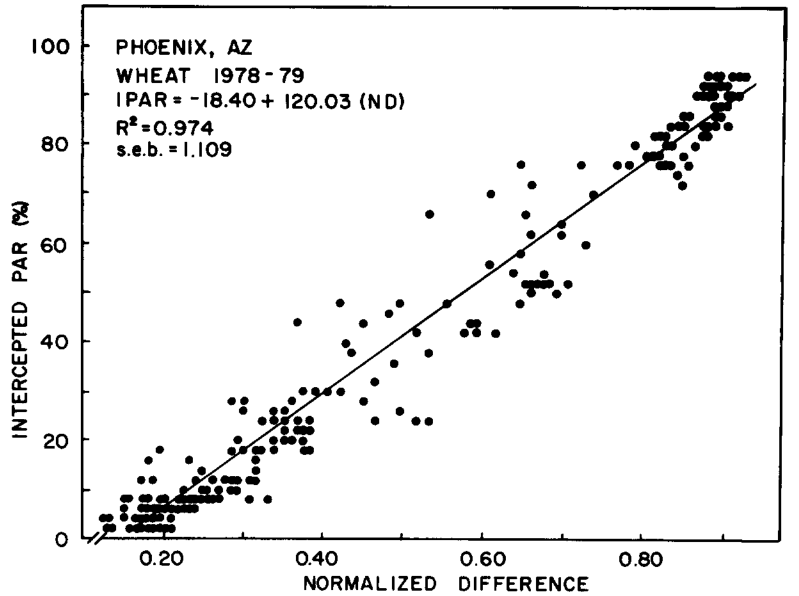

FIGURE 7. Normalized difference relationship to PAR interception in 1978–79 for the growth phase of Produra wheat.

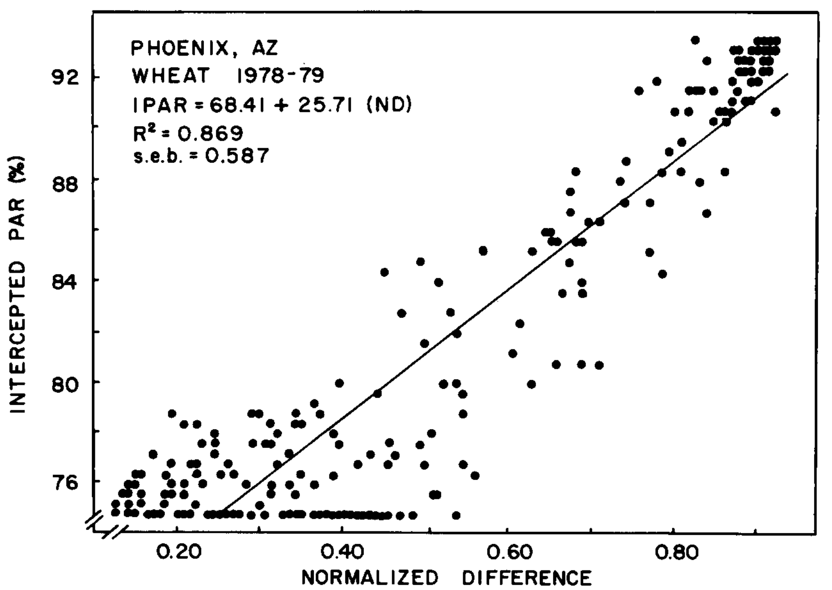

FIGURE 8. Normalized difference relationship to PAR interception for the senescence phase for the 1978–79 planting dates of Produra wheat.

are very similar and the overall statistical relationship would not be significantly changed.

Evaluation of the PAR interception model

Normalized difference relationships from Table 3 were used to estimate the interception measured on wheat by Hipps et al. (1983). The data given by Hipps et al. were matched to spectral reflectance measurements made over the plots with MSS bands 5 and 7, and Thematic Mapper bands 3 and 4. In all cases the agreement was within 10%. The relationship appears to work for TM bands as well as MSS bands. However, these comparative data sets were collected only in the later stages of growth when the interception values were above 80%.

When bare soil reflectance values from Manhattan, Kansas and Davis, California were placed in the model, the predicted interception was almost zero, suggesting that the model as defined is not sensitive to these soil types. The model needs further evaluation on different soil types and cultural practices to fully test its sensitivity to these parameters.

Summary and Conclusions

Calculated values of PAR interception and greenness or normalized difference were related throughout the wheat growing season. Both of these spectral models were related to PAR interception, although two different relationships are required to represent preheading and postheading phases of the plant. Greenness and normalized difference both follow the PAR interception closely and begin at the bare soil value but do not return to that value when the crop is mature. The value at maturity of either spectral model is a function of the canopy density or biomass at the end of the season. Pinter et al. (1981) related this behavior to the grain yield of wheat, and the relationships presented in this paper suggest that the normalized difference provides an estimate of PAR interception.

Normalized difference appeared to give slightly higher R^2 values than greenness in its linear correlation with PAR interception. However, greenness has been found to be less sensitive to the soil background and row direction (Kollenkark et al., 1982). This suggests that normalized difference with no empirical coefficients attached is preferable over a calculation of greenness. It is possible that Thematic Mapper bands could be utilized in the normalized difference model without loss of sensitivity. This aspect needs further evaluation over different crops and locations throughout a growing season.

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